Quasi-Static Modelling of the Ionosphere-Magnetosphere Coupling: Ionospheric Localized Effects

Echim M.[1-2], Roth M.[2], De Keyser J.[2]
[1]Institute for Space Sciences Bucharest
Romania

[2]Belgian Institute for Space Aeronomy Brussels
Belgium

echim@venus.nipne.ro

ABSTRACT

The physical processes that take place in the auroral ionosphere (activation of auroral arcs at various spatial scales, plasma irregularities, non-homogeneities of the electric conductivity) are linked with the dynamics of the distant magnetosphere; the same geomagnetic field lines connect the polar ionosphere and the distant magnetosphere. Inside the magnetosphere the plasma parameters (temperature, density, bulk velocity) are non-uniform. We develop a stationary model that predicts the amplitude of the ionospheric perturbations corresponding to magnetospheric sheared flows. In this study we investigate the sheared plasma flows encountered close to the outer magnetospheric boundary layers. The main components of the model are:(i) a kinetic tangential discontinuity that plays the role of a magnetospheric generator; (ii) a current-voltage relationship describing the flux of generator particles precipitating into the ionosphere as well as the flux o the ionospheric outflow and (iii) a simple model of the topside ionosphere. The solution of the current continuity equation at topside ionosphere gives the latitudinal variation of the ionospheric electrostatic potential and of the field aligned potential drop. Our model provides a tool for evaluating the ionospheric effects of a distant dynamic magnetosphere. Ionospheric perturbations (especially conductivity irregularities) constitute a threat for satellite communications (including GPS) as well as for radio-wave navigation systems.

1. INTRODUCTION

Monitoring of the auroral activity is seen as a powerful tool to investigate the global state of the terrestrial magnetosphere. Indeed, due to the topology of the geomagnetic field, large parcels of the high altitude magnetosphere map along magnetic field lines into regions of much smaller latitudinal width at ionospheric altitudes of the order of 10^2 km. The mapping and the physical processes involved are still subject of investigation. The magnetosphere-ionosphere coupling was long seen as a possibility to remote sense the magnetospheric state. However, the development of space weather predicting tools rise the interest for finding key magnetospheric regions to be visited by satellite sentinels in order to find vital information concerning the ionospheric perturbations produced by increased magnetospheric activity.

Ionospheric irregularities, scintillations and non-homogeneities constitute a thread for the accuracy of the GPS signal receiving and for some sophisticated naval communication systems. Understanding and modelling of the fundamental physical processes taking place in the magnetosphere-ionosphere system contribute to the advancement of our capabilities to assess and eventually predict natural space hazards, but also to develop measures to protect the vulnerable technologies.

Echim, M.; Roth, M.; De Keyser, J. (2006) Quasi-Static Modelling of the Ionosphere-Magnetosphere Coupling: Ionospheric Localized Effects. In *Emerging and Future Technologies for Space Based Operations Support to NATO Military Operations* (pp. P4-1 – P4-8). Meeting Proceedings RTO-MP-RTB-SPSM-001, Poster 4. Neuilly-sur-Seine, France: RTO. Available from: http://www.rto.nato.int/abstracts.asp.

Report Documentation Page	Form Approved OMB No. 0704-0188

1. REPORT DATE **01 DEC 2006**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Quasi-Static Modelling of the Ionosphere-Magnetosphere Coupling: Ionospheric Localized Effects**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Institute for Space Sciences Bucharest Romania**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES **See also ADM202419., The original document contains color images.**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Sheared plasma flows are magnetospheric processes whose ionospheric fingerprint seem to be among the most effective for the magnetosphere-ionosphere coupling. In this paper we use the definition of a sheared flow as the plasma state for which the normal component (with respect to B-field) bulk velocity is non-uniform in the direction perpendicular to the local magnetic field. We have identified two major classes of sheared plasma flows: (a) flow at small and medium scales in the tail of the magnetosphere, known as "fast plasma flows", "bursty bulk flows" or "beamlets"[1]-[2]; (b) sheared flows of extraterrestrial plasma in the outer boundary layers of the Earth's magnetosphere [3]-[4]. In this paper we investigate the latter class, notably the type of sheared velocity encountered at the interface between the Low Latitude Boundary Layer (LLBL) and the Plasma Sheet (PS).

2. KINETIC MODELLING OF SHEARED PLASMA FLOWS

We will consider the boundary layer forming at the interface between a plasma with density N_{m1}, temperature T_{m1}, at rest and a plasma with density N_{m2}, temperature T_{m2} in motion with the velocity V_2. We assume that inside the boundary layer all the variables depend only on the coordinate normal to the surface of the boundary layer. The solution is found for the case when the normal component of the magnetic field is equal to zero. Thus the boundary layer can be described as a tangential discontinuity (TD). A Vlasov equilibrium solution is find for a TD with plasma parameters typical for the sheared plasma flows at the interface between LLBL and PS. We consider that all the plasma variables and fields depend only on the x-coordinate, normal to the TD. We will not give here details concerning the kinetic modelling of TDs, they are well documented in the literature [5] – [7].

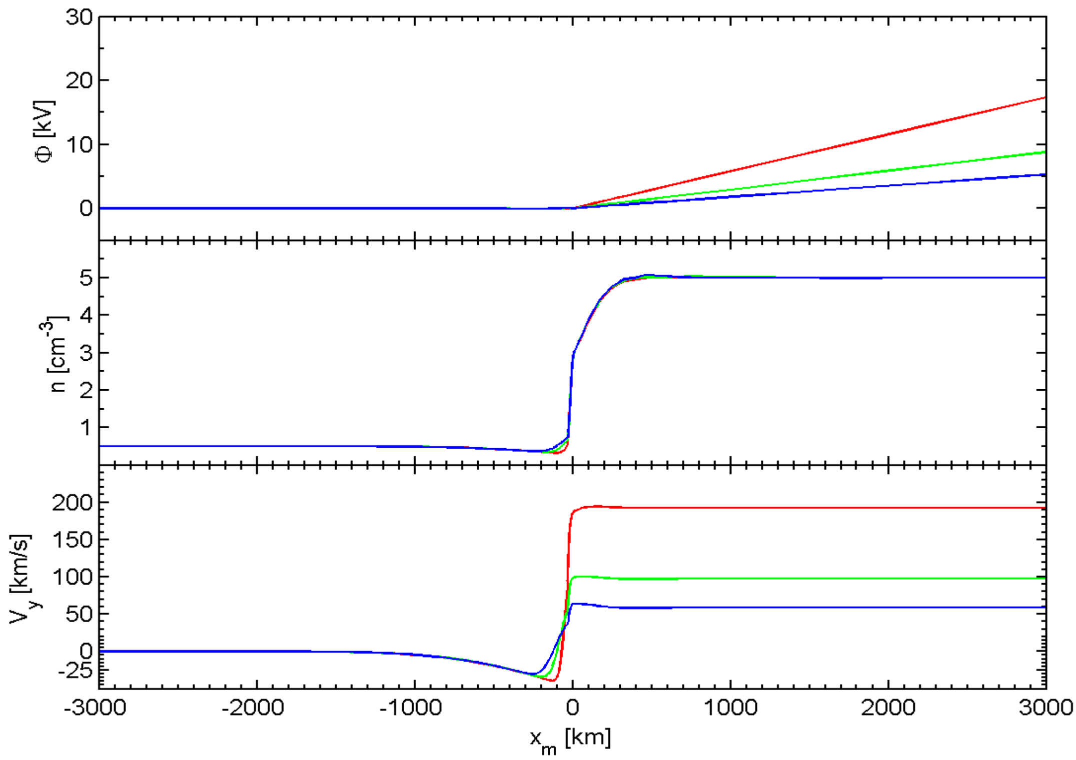

Figure 1: Kinetic tangential discontinuity (TD) solution for the transition between a plasma at rest (left hand side) and a plasma moving in the y-direction (right hand side). Three different plasma bulk velocity are considered ($V_x = V_z = 0$ everywhere). The TD is centred in x=0 and is parallel to the yOz plane. The panels show the variation with the x-coordinate (normal to the TD surface) of the electrostatic potential (Φ), number density (n) and plasma bulk velocity in the y direction. The asymptotic values were chosen in a range typical for the LLBL-PS regions of the terrestrial magnetosphere.

Let us briefly recall the main principles. When no time dependent effects are considered, the dynamics of the plasma particles is completely determined by the constants of motion. Should we consider only one spatial coordinate (which is the case here) the three constants of motion are: the total energy (H) and the two components of the canonical momentum corresponding to the ignorable coordinates (p_y, p_z). Then the solution for the Vlasov equation of plasma state in the stationary case may be written as any mathematical positive function of H, p_y and p_z. In the kinetic model of the TD this function is chosen on the grounds of mathematical simplicity and to satisfy the asymptotic conditions that describe the problem. In our case the asymptotic conditions are that the plasma moves on one side and stays at rest on the other side of the transition layer. It is possible to find piecewise Maxwellian distribution functions as those described by Roth et al. [5]or Echim and Lemaire [7] for various types of transitions. In this study we use the one-dimensional TD model developed in [5].

Figure 1 shows the solution obtained for a moving plasma, having a density of 5 cm^{-3}, an electron temperature of 10 eV, a proton temperature of 100 eV typical for the outer layers of the terrestrial magnetosphere, like the LLBL. It interfaces a stagnant plasma with a density of 0.5 cm^{-3} , an electron temperature of 200 eV, a proton temperature of 1000 eV, typical for the terrestrial plasma sheet. The effects of increasing the plasma velocity are also illustrated by figure 1. Note the variation of the electrostatic potential (and of the corresponding electric field) as well as the variation of the transition thickness. Note also the flow reversal (change of direction of the bulk velocity) inside the boundary layer, for -11000 km < x_m < 0. This is an interesting feature as in-situ satellite measurements in the outer magnetospheric layers show often this type of flows. The distributions of the potential, density and temperature from the kinetic model are used as input parameters for the quasi-static model of the magnetosphere-ionosphere coupling, as explained in the next section.

3. QUASI STATIC MAGNETOSPHERE - IONOSPHERE COUPLING

The outer magnetospheric boundary layers with sheared plasma flows are connected to the ionosphere by the geomagnetic field lines. The magnetospheric plasma is less dense and has a high temperature while the ionospheric plasma is (orders of magnitude) much denser but have a significantly smaller temperature. The two plasmas are in permanent contact through the “superconductor” magnetic field lines. The equilibrium solution for this system of two constituent plasmas has been studied and kinetic solutions have been found [8], [9]. These solutions are sometimes called “exospheric” since they model the transition from a collisional (ionospheric) regime to a collisionless (magnetospheric) state. Exospheric models provide analytical expressions for the flux of particles emerging from both (magnetospheric and ionospheric) sides along the magnetic lines of force. These expressions give the current – voltage relationship, of utmost importance for modelling the magnetosphere – ionosphere coupling since they give the density of the field aligned current, $j_{\|}$, as a function of the potential difference, $V_{\|} = \Phi_i - \Phi_m$, between the ionosphere and manetosphere.

Lyons [10], [11] was among the first to notice that given a distribution of the magnetospheric potential and knowing the current voltage relationship, $j_{\|}(V_{\|})$, one can write the equation of current continuity for the topside ionosphere:

$$j_{\|}\left(x_i, \Phi_i - \Phi_m\right) = -\frac{d}{dx_i} I_P = \frac{d}{dx_i}\left(\Sigma_P (x_i, \Phi_i - \Phi_m) \frac{d\Phi_i}{dx_i} \right) \tag{1}$$

to find the latitudinal distribution, $\Phi_i(x_i)$, of the ionospheric potential. In equation (1) Σ_P is the Pedersen conductance; it can be a function of the flux of precipitating energy, thus a function of the accelerating potential drop between the magnetosphere and the ionosphere.

Roth, Evans and Lemaire [12] have shown that tangential discontinuities formed at the interface between sheared flows (of the type briefly described in the previous section) are a source of an electromotive force connected to the ionosphere by a dissipative current system. In this study we use these earlier ideas to develop a quantitative model that computes the latitudinal distribution of the ionospheric potential (and all the related quantities, like field aligned current density, the flux of precipitating energy, height integrated Pedersen conductivity). Instead of the ad-hoc potential distributions used in the past [10]-[11] we introduce a potential distribution Φ_m, computed by the kinetic model of a tangential discontinuity. The magnetospheric potential varies with the asymptotic velocity, density and/or temperature. Therefore we can study the amplitude of the corresponding ionospheric effects as a function of these magnetospheric parameters.

In Plate 1 we show the diagram of the numerical scheme developed to find the solution of the equation (1). The current continuity is a nonlinear, second order differential equation that is solved by imposing a two-point boundary condition: $V_{||}(+/- x_{iL}) = 0$, where x_{iL} stands for the two boundary coordinates. Note that the x_i coincides with the latitude. The model provides a North-South profile of the ionospheric potential. The ionospheric input parameters (density and temperature of the constituent species) are chosen according to the average values of the density, temperature and composition observed at 200 kilometers altitude and 70^0N latitude, during night time. We chose to compute the ionospheric effects at 200 kilometers altitude since it is this altitude where they will be most effective. The model however can produce results for a broader range of ionospheric altitudes, including those intersected by polar satellites.

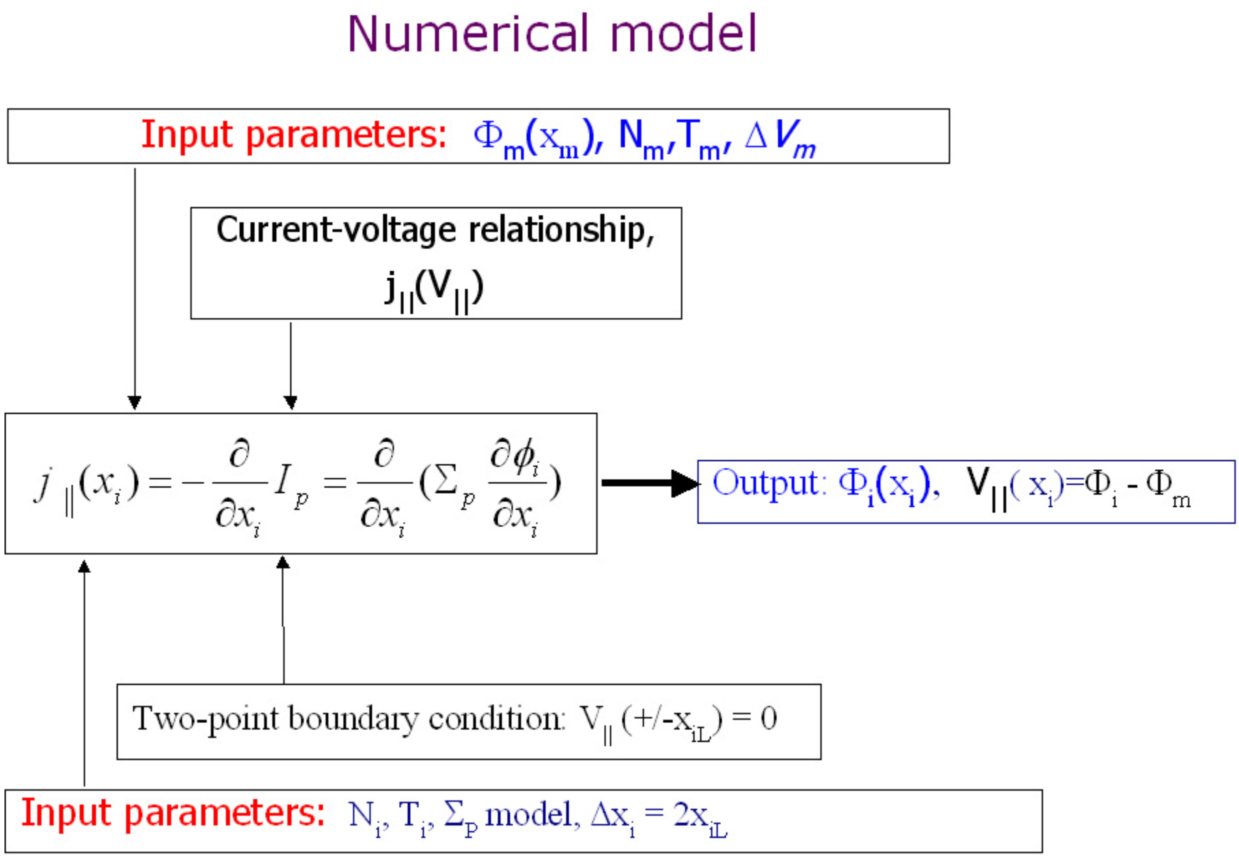

Plate 1. Diagram of the numerical model developed to compute the ionospheric effects induced by magnetospheric sheared flows. Index "*m*" and "*i*" stand for respectively magnetospheric an ionospheric parameters. The distribution of the magnetospheric potential, Φ_m, is computed by the kinetic model of a tangential discontinuity. The current-voltage relationship is adapted from the exospheric models of the polar wind. The equation of current continuity is solved numerically by a finite differences scheme based on an iterative Newton sequence.

We consider three different populations. (A) Magnetospheric electrons are accelerated by a positive potential drop ($\Phi_i - \Phi_m > 0$) along magnetic field lines; they are decelerated by the mirror force since the magnetic field intensity increase with decreasing altitude and the magnetic moment, $\mu = mv_{perp}/\mu_0 B$, is conserved. Magnetospheric electrons form the precipitating population that carry the energy from the magnetosphere to the ionosphere. These particles have the major contribution to the upward (or direct) current of the auroral circuit. (B) Ionospheric electrons are much more numerous at 200 km altitude. They are decelerated by the positive potential drop and are accelerated by the mirror force. These particles contribute to the downward (or return) current, their partial current density is very small for $V_{\|}$>10 Volt. (C) Ionospheric ions are accelerated by both the electrostatic and mirror force. They contribute to the upward leg of the auroral circuit. Since their energy is less than 0.1 eV and the density of ~10^3 cm^{-3}, their partial current density is of the order of 10^{-7} $\mu A/m^2$, one order of magnitude less than the contribution of the magnetospheric electrons. The sum of the partial currents due to the species (A), (B) and (C) constitutes the total current density (as a function of Φ_i and Φ_m) to be plugged into the equation (1).

Figure 2 summarises the results obtained for a series of values of the velocity shear, imposed at the magnetospheric side. The region with sheared flow extends over 11000 kilometers in latitude at a magnetospheric altitude of 90000 kilometers. The solution of the current continuity equation is computed at 200 km altitude. The latitudinal profile of the magnetospheric plasma variables was mapped into the ionosphere by multiplying the magnetospheric coordinate x_m by the magnetic compression factor $\sqrt{B_m / B_i}$ with B_m, B_i the magnetic induction at respectively magnetospheric and ionospheric altitude. The latitudinal width of the solution in the ionosphere is roughly 600 km.

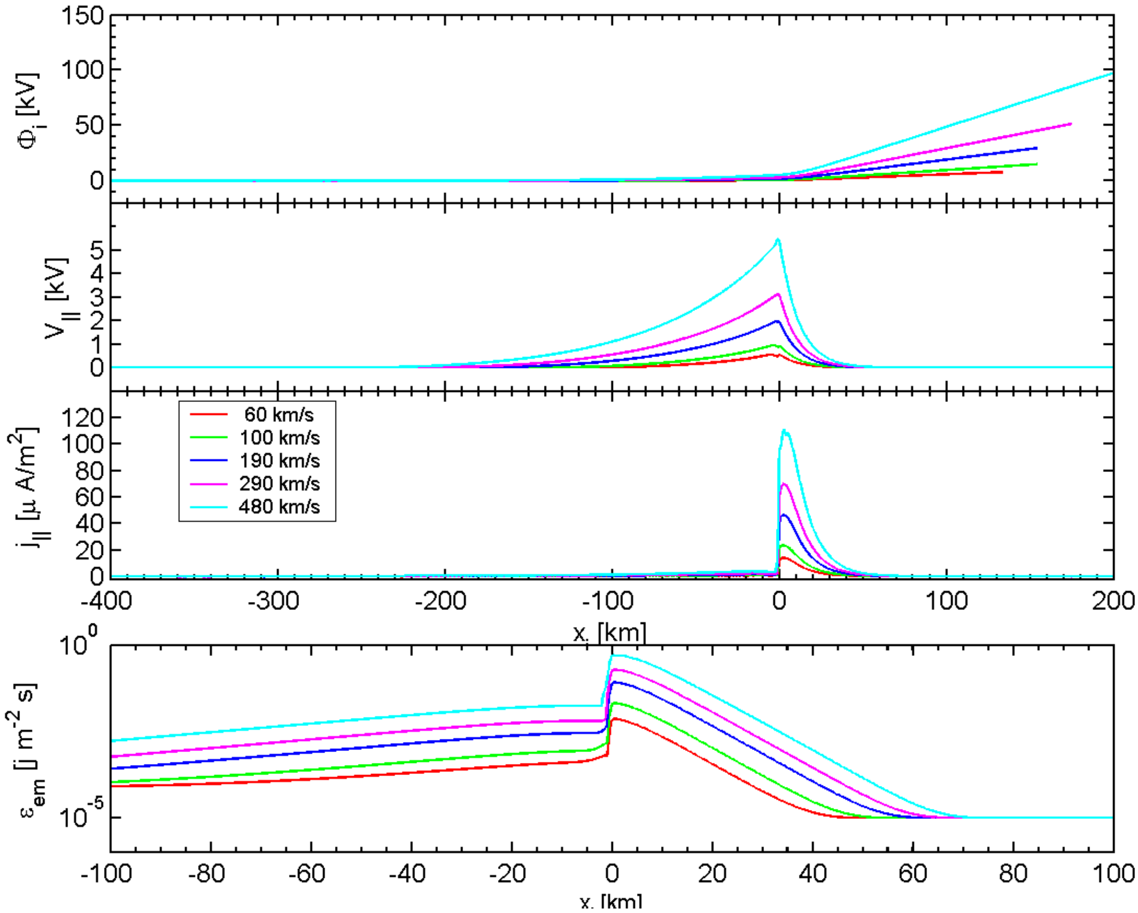

Figure 2. Ionospheric quantities obtained for a sheared magnetospheric plasma flow described by a TD model illustrated in Figure 1. All the quantities are mapped at the ionospheric altitude of 200 kilometers. The first three panels show on a linear scale: the ionospheric electrostatic potential, the field aligned potential drop, the field aligned current density. Fourth panel shows a detail on a logarithmic scale of the flux of precipitating energy.

For each value of the shear of the plasma bulk velocity it was found a positive field aligned potential drop. This potential structure accelerates the magnetospheric electrons. The amplitude increase with increasing velocity. Within a broader ionospheric region, expanding over a distance of 200-250 km, the parallel potential drop takes moderate values (less than 400 V) when the velocity is also moderate (< 300 km/s). There is however a narrower region where $V_{||}$ reaches values of the order of kilovolt even for smaller velocity shears at the magnetospheric side. The later region is considered to be the site of auroral activation due to precipitating magnetospheric electrons.

One important feature of the solution is the formation of a narrow sheet of field aligned current with a thickness at half height of the order of 10 to 25 km. The actual width depends on the velocity shear. The field aligned current sheet widens for larger shear of the magnetospheric plasma bulk velocity. The current density increase with the shear as well as the peak of the field aligned potential drop. The sharp jump observed both in the current density and precipitating energy flux (see below) coincides with the jump in the plasma density of the magnetospheric TD.

Inside the field aligned current sheet there is an even narrower region where the flux of precipitating energy is orders of magnitude greater than in the neighbouring ionospheric domain. Note also that the profile of the precipitating energy, ε_m, gives also information about the perturbation produced by incoming electrons to the ionospheric Pedersen conductivity since the following empirical equation holds: .

A detail of this region is plotted on a logarithmic scale in the lower panel of Figure 2. Assuming that the luminous intensity of the visible aurora is proportional to the incident flux of energy due to precipitating particles, one notes that the auroral arcs are brighter for larger shear of magnetospheric plasma velocity. The thickness of the arcs varies from several to ten-fifteen kilometers. The brighter arcs are also the wider. The scaling of the arcs identified in this study must be taken with some caution since only one parameter (the plasma velocity) has changed value during the computations discussed above. It is likely that other parameters (density, temperature, magnetic field ratio) play an equally important role for scaling of discrete auroral arcs. Investigation of these complementary effects will be the task of our future investigation.

SUMMARY AND CONCLUSIONS

Magnetospheric sheared flows are a generator of electromotive force. The source of energy is the external driver that sustains the flow and the gradients of velocity, density and/or temperature. If this driver have enough power to sustain such gradients over time intervals longer than the Alfven travel time between the magnetosphere and ionosphere one can neglect time dependent effects and look for a steady state solution.

In the stationary case, kinetic solutions for sheared flows in the generator can be found for a class of transitions denoted tangential discontinuities. These solutions provide the profile of the electrostatic field, density and temperature given the asymptotic conditions for the plasma state. On the other hand the parallel flux of charged particles emerging both from the magnetospheric generator and the ionosphere can be computed analytically as function of the potential difference between the generator and the load (ionosphere). The fundamental equation that couples all these quantities is the current continuity equation written on top of the ionosphere. Numerical solutions of this equation have been found by imposing the two-point boundary condition stating that the parallel potential drop is equal to zero at the left and righ hand sides.

A positive potential drop with a peak of the order of kiloVolt has been found in each of the cases investigated here. The maximum of the potential drop ranges between 800 and 5500 Volt when the shear of the velocity varied from 60 to 480 km/s. The region of strong field aligned potential drop widens with increasing velocity.

Field aligned currents flow towards the ionosphere in a much narrower band. A strong jump in the parallel current density coincides with the number density jump observed for the magnetospheric transition layer. The maximum of the field aligned density span a broad range of values, from 15 $\mu A/m^2$ to 110 $\mu A/m^2$, for velocity speeds in the range 60 to 480 km/s. The thickness of the field aligned current sheet ranges between 10 and 25 km at 200 km altitude. The region where the energy precipitation reaches significant values is even narrower. Our model of quasi-static coupling between the magnetosphere and ionosphere predicts auroral arcs with thickness of several kilometers.

This study demonstrates that the sheared plasma flows in the outer layers of the magnetosphere, driven by the cuasi-permanent interaction with the solar wind, provide the required energy for activation of auroral discrete arcs. It also shows how the scale of the ionospheric perturbations vary with the amplitude of the velocity shear in the distant magnetosphere. The model demonstrates its usefulness for quantitative analysis of the coupled magnetosphere-ionosphere system.

REFERENCES

[1] Cao, J.B., Y.D. Ma, G. Parks, H. Reme, I. Dandouras, R. Nakamura, T.L., Zhang, Q. Zong, E. Lucek, C.M. Carr, Z.X. Liu, G.C. “Joint observations by Cluster satellites of bursty bulk flows in the magntotail”, Journal of Geophysical Research, 111, A04206, 2006-08-17

[2] Grigorenko, E.E., Fedorov, A., Zelenyi, L.M., “Statistical study of transient plasma structures in magnetotail lobes and plasma sheet boundary layer: Interball-1 observations”, Annales Geophysicae, 20, 329, 2002

[3] Lundin, R., Evans, D., “Boundary layer plasmas as a source for high-latitude, early afternoon, auroral arcs”, Planetary Space Science, 33, 12, 1389, 1985

[4] Phan, T.D., D. Larson, J. McFadden, R.P. Lin, C. Carlson, M. Moyer, K.I. Paularena, M. McCarthy, G.K. Parks, H. Reme, T.R. Sanderson and R.P. Lepping, “Low-latitude dusk flank magnetosheath, magnetopause, and boundary layer for low magnetic shear: Wind observations”, Journal of Geophysical Research, 102, A9, 19883, 1997

[5] Roth, M., J. De Keyser, M.M. Kuznetsova, “Vlasov theory of the equilibrium structure of tangential discontinuities in space plasmas”, Space Science Reviews, 76, 251, 1996

[6] De Keyser, J., M. Roth, “Equilibrium conditions for the tangential discontinuity magnetopause”, Journal of Geophysical Research, 102, 9513, 1997

[7] Echim, M., J., Lemaire, “Two-dimensional solution for a collisionless plasma jet across transverse magnetic field lines with a sheared bulk velocity”, Physical Review E, 72, 036405, 2005

[8] Lemaire, J. and M. Scherer, “Simple model for an ion-exosphere in an open magnetic field”, Physics of Fluids, 14, 1683, 1971

[9] Knight, L., “Parallel electric fields”, Planetary and Space Sciences, 21, 741, 1973

[10] Lyons, L.R., “Generation of large-scale regions of auroral currents, electric potentials and precipitation by the divergence of the convection electric field”, Journal of Geophysical Research, 85, 17, 1980

[11] Lyons, L.R., “Discrete aurora a the direct result of an inferred high altitude generating potential distribution”, Journal of Geophysical Research, 86, 1, 1981

[12] Roth, M., D. Evans, J. Lemaire, “Theoretical structure of a magnetospheric plasma boundary: application to the formation of discrete auroral acs”, 98, 11411, 1993